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Calculation of Airborne Radioactivity Hazard from Machining Volume-Activated Materials

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Calculation Of Airborne Radioactivity Hazard From Machining Volume-Activated Materials

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Abstract

When evaluating a task involving the machining of volume-activated materials, accelerator health physicists must consider more than the surface contamination levels of the equipment and containment of loose shavings, dust or filings. Machining operations such as sawing, routing, welding, and grinding conducted on volume-activated material may pose a significant airborne radioactivity hazard to the worker. This paper presents a computer spreadsheet notebook that conservatively estimates the airborne radioactivity levels generated during machining operations performed on volume-activated materials. By knowing (1) the size and type of materials, (2) the dose rate at a given distances, and (3) limited process knowledge, the Derived Air Concentration (DAC) fraction can be estimated. This tool is flexible, taking into consideration that the process knowledge available for the different materials varies. It addresses the two most common geometries: thick plane and circular cylinder. Once the DAC fraction has been estimated, controls can be implemented to mitigate the hazard to the worker.

Introduction

Accelerator facilities are capable of producing four general types of radioactivity: airborne, surface contamination, liquid system activation, and volume activation. Much of the airborne radioactivity is comprised of short-lived spallation products due to particle interactions with the air in the enclosures (^{7}Be, ^{13}N, ^{15}O, ^{11}C, ^{38}Cl, and ^{39}Cl) [Butala, Baker and Yurista 1989; IAEA 1979; IAEA 1988; Patterson and Thomas 1973]. Configuring ventilation systems appropriately

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and imposing delays prior to enclosure access allow for decay of these nuclides and essentially eliminate the airborne radioactivity hazard to the environment and workers.

Surface contamination also poses little radiological hazard in accelerator facilities. Much of the surface contamination is comprised of the activated dust and grease on components in the enclosures in areas of high beam loss. Basic housekeeping techniques help to minimize the production and spread of contamination. Radionuclide concentrations in wipe surveys conducted in accelerator enclosures indicate that the surface contamination levels are not high enough to result in airborne radioactivity and typically decay rapidly after operations have ceased.

Liquid systems, such as cooling water systems, are also subject to activation. Activation products, such as ^{13}N, ^{11}C, and ^{7}Be [IAEA 1979; IAEA 1988], are removed from the system through a properly configured filtration system. The filters may be held for a period of time until relatively short-lived activation products decay or may be properly disposed of as radioactive waste. The activation products remaining in the system may be easily quantitifed through liquid scintillation or gamma spectral analysis.

Finally, accelerator operation results in volume activation of solid materials contained within the enclosures. The radionuclides present and the levels of radioactivity in these items are dependent upon many factors, including the type of incident particle, incident particle energy, length of irradiation, decay periods, and target composition. Typical radionuclides found in solid materials around the accelerator include ^{7}Be, ^{11}C, ^{22}Na, ^{26}Al, ^{54}Mn, ^{59}Fe, ^{58}Co, and ^{60}Co [IAEA 1979; IAEA 1988; Patterson and Thomas 1973]. On occasion, it may be necessary to perform welding, grinding, or cutting operations to repair the items or package them for waste disposal. Because of the volume activation of these items, these operations can produce airborne radioactivity.

The materials can be of any range of shapes, sizes, and activity levels and there is little information available to relate the dose rate of the material, an easily measured quantity, to the airborne radioactivity concentration during cutting or other similar activities. Since sampling and subsequent analytical analysis of these materials is both time-consuming and expensive, a more practical approach needs to be developed to help accelerator health physicists evaluate the airborne radioactivity hazard and thus, the potential internal exposures.

This paper introduces a computer spreadsheet notebook that conservatively estimates the airborne radioactivity levels generated during machining operations performed on volume-activated materials. By knowing (1) the size and type of materials, (2) the dose rate at a given distance, and (3) limited process knowledge, the Derived Air Concentration (DAC) fraction can be estimated. The inhalation DAC is the airborne concentration of a radionuclide that if breathed by the average worker for a working year of 2000 hours would result in an effective dose of 0.05 Sv. This tool is flexible, taking into consideration that process knowledge available for different materials varies. It addresses two common geometries: thick plane and circular cylinder. Once the DAC fraction has been estimated, controls can be implemented to mitigate the hazard to the worker.

Specific Activity In Material

To relate the airborne radioactivity levels during the cutting operation to the dose rate of the material, the specific activity in the material must be calculated. Dose rate is a readily measured quantity that is a function of the source geometry, the source activity, and the distance from the source. A graphical depiction is included in Fig. 1. Given that 37 Gy is the absorbed dose to tissue from an exposure of 1 C kg^{-1} air, the relationship between dose rate and specific activity may be expressed by the following equation [Cember 1983]:

$$C_v = \frac{\mu \dot{D}_i}{37\pi\, \Gamma_i \left(1 - e^{-\mu t}\right) \ln\left(\frac{r^2 + h^2}{h^2}\right)} \quad \frac{\text{MBq}}{\text{m}^3} \qquad [1]$$

where C_V = specific activity of radionuclide i

$\dot{D}_i$ = dose rate due to radionuclide i (Gy hr^{-1})

Γ_i = specific gamma ray constant for radionuclide i (C m^2 MBq^{-1} kg^{-1} hr^{-1})

r = effective radius of disc (m)

h = distance at which measurement is taken (m)

t = thickness of material (m)

μ = linear attenuation coefficient of material (m^{-1})

More often than not, more than one radionuclide contributes to the measured dose rate. Thus,

$$\dot{D}_T = \sum_i \dot{D}_i \qquad [2]$$

where $\dot{D}_T$ = dose rate measured.

If the material's fractional radionuclide composition is known or can be estimated, the specific activity in MBq m^{-3} can be calculated from the measured exposure rate. The current spreadsheet is limited to calculating the specific activity in iron, copper, stainless steel and aluminum. These are the most common materials encountered in the accelerator environment that would require subsequent machining. However, the user who is knowledgeable of spreadsheets does have the capability of adding other materials.

As stated previously, exposure rate is also a function of source geometry. Equation 1 was derived assuming right circular cylinder geometry or a disc source. However, thick plane geometry is also prevalent. To accommodate this, the spreadsheet was designed to accept either the radius of the right circular cylinder or the rectangular dimensions of the slab. If rectangular dimensions are used, an effective radius is calculated. The effective radius is the radius of the circle with the same area as the face of the thick plane.

Airborne Radioactivity Levels

Once the specific activity of the material is determined, an estimate can be made of the airborne radioactivity concentrations that would result from machining the material by using Equation 3.

$$\text{Conc. [air]}\left(\frac{\text{Bq}}{\text{m}^3}\right) = \frac{\text{Conc. [steel]}\left(\frac{\text{Bq}}{\text{m}^3}\right) * \text{Suspension Factor}\left(\frac{\text{g steel}}{\text{m}^3\ \text{air}}\right)}{\text{Density [steel]}\left(\frac{\text{g}}{\text{m}^3}\right)} \qquad [3]$$

Assuming all of the activity present in the air volume is due to the cutting operation, the specific activity of the air is then proportional to the specific activity of the material being cut. This method is independent of cut size or the volume into which the activity is released. It does, however, assume that the material is uniformly activated. This is not generally the case, but it does add a measure of conservatism into the calculation since the dose rate, in practice, is measured at the most radioactive spot. Another implied assumption is that there is immediate mixing within the volume of air.

The suspension factor is a measure of the particulate loading in the air or the mass concentration in air of the solid material released by the cutting process. An option is provided in the spreadsheet to allow the user to choose a suspension factor that would be a judicious estimate of particulate loading considering the machining operation. For instance, the Threshold Limit Value (TLV) for welding fumes is 5 mg m^{-3}, so that would be a reasonably conservative suspension factor for welding operations [ACGIH 1995].

DAC Fraction

The DAC fraction is then calculated by dividing the airborne radioactivity concentration of the radionuclide by its associated inhalation DAC. By summing the DAC fractions over the radionuclides, a determination can be made for posting, monitoring, respiratory protection and other appropriate controls. Both Part 835 and Part 20 of Title 10 of the Code of Federal Regulations outline the applicable requirements for facilities under jurisdiction of the U.S. Department of Energy (DOE) and the U.S. Nuclear Regulatory Commission (NRC) [10CFR835 1993; 10CFR20 1991].

Methods and Measurements

A series of spreadsheets were designed using Quattro Pro for Windows Ver. 5.0, but also saved in Lotus 1-2-3 and Excel. Figure 2 shows one of the spreadsheets. Most of the input is self-explanatory. Units in the spreadsheet remain in special units as they are reflective of the posting and reporting requirements of the DOE and the NRC [10CFR835 1993; 10CFR20 1991]. In addition to DAC fraction, the spreadsheet also calculates other information, including dose rate.

To test the validity of the methodology employed, air sample and dose rate measurements, taken during the welding of a 0.3175 cm thick aluminum component scraped by ~1% of a 10μA primary electron beam at about a 50 milliradian angle, were compared to the spreadsheet estimates. The "Eff. Thickness Activation" and "% activation" cells in the spreadsheet account for the irradiation conditions and are used to compute the fraction of full shower developed which is related to the component activity. As the operation was welding, a suspension factor of 5 mg m^{-3} was used.

The absorbed dose rate measured during the work was 1.0 mrad hr^{-1}, as compared to the estimated dose rate of 1.21 mrad hr^{-1}. Air sample results indicated ^{7}Be and ^{24}Na with respective specific activities of $(2.7 \pm 1.2) \times 10^{-11}$ μCi ml^{-1} and $(6.4 \pm 2.2) \times 10^{-12}$ μCi ml^{-1}, compared to those predicted of 1.60×10^{-12} and 4.01×10^{-11} μCi ml^{-1}. The predicted value for ^{7}Be is significantly below that measured, but is likely to be in error due to external adherence of ^{7}Be from oxygen spallation in moist air. Estimation of the ^{24}Na component is shown to be conservative. No detectable radionuclides were seen in breathing zone samples taken at the same time.

Conclusions

It was important to design a user-friendly tool to conservatively estimate the airborne radiological hazard from machining volume-activated radioactive material. This spreadsheet gives the accelerator health physicist a reference point that can be used in imposing controls to minimize airborne radioactivity hazards during such work. Initial measurements have shown this tool is reasonable and conservative, but it is not meant to replace prudent monitoring, controls and/or surveying. Other users can, and should, modify the spreadsheet to include other materials and material compositions, suspension factors, and even other geometries so that it can best meet their institution's specific needs. For interested parties, the spreadsheet may be obtained by contacting one of the authors.

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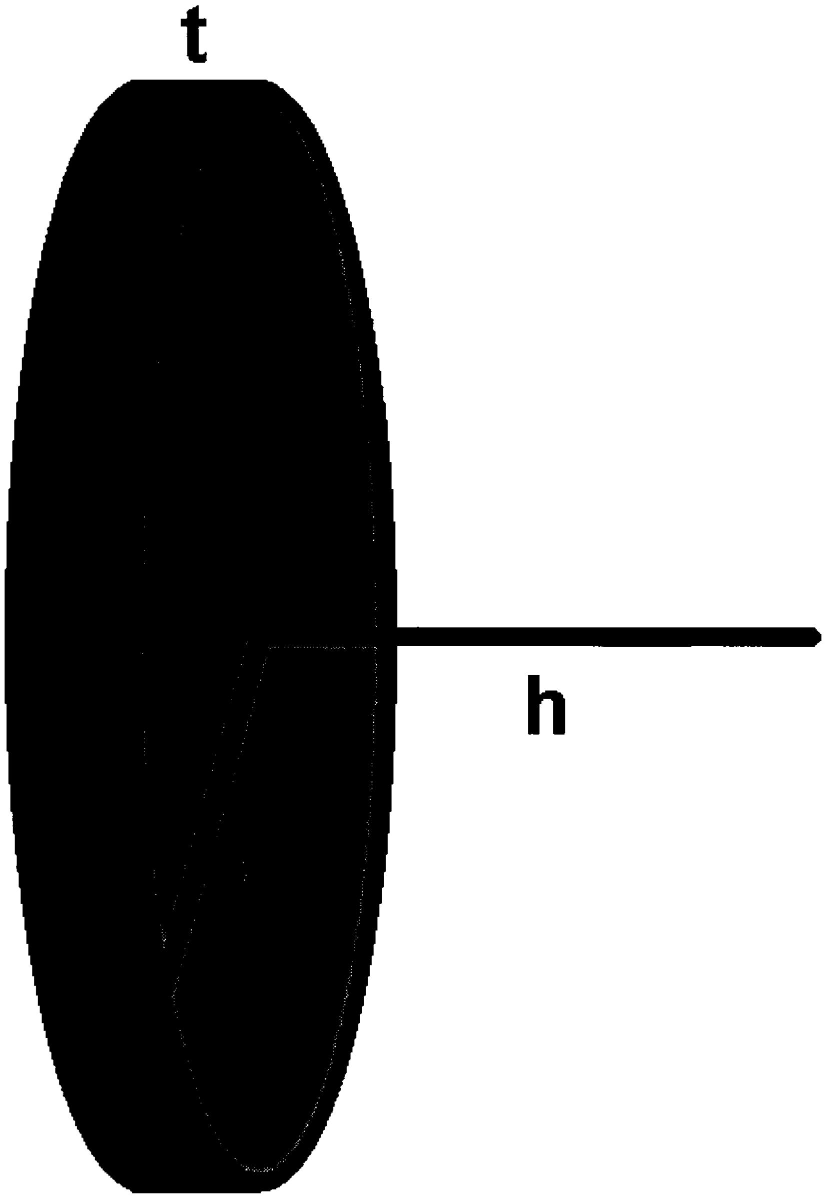
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Beam Parameters

Kinetic Energy	0.8 GeV	28.36% activation	Fe,SS
Beam Current	0.1 uA	33.48% activation	Cu
run time	48 hours	6.38% activation	Al
time off	24 hours		
Eff. Thickness Activation	6.35 cm		

Suspension Factor

5 mg/m^3

Dimensions

thickness	0.3175 cm
width	61 cm
length	1000 cm
eff. radius	139.380 cm
volume	0.019 m^3
distance	30 cm

	Initial Activity (Ci/uA)	Current Activity (Ci)	Specific Activity (Ci/m^3)	% of total	effective linear coeff (cm^-1)	Tissue Dose Rate (rad/hr)	Metal Specific Activity (Ci/m^3)	Air Specific Activity (uCi/mL)	%DAC
Aluminum						**1.21E-03**			
Al-27 (g,sp) Be-7	1.70E-04	1.67E-05	8.64E-04	3.82%	2.33E-01	7.51E-07	8.64E-04	1.60E-12	0.00%
Al-27 (g,sp) C-11	2.60E-03	1.16E-25	6.01E-24	0.00%	2.26E-01	1.06E-25	6.01E-24	1.11E-32	0.00%
Al-27 (g,sp) N-13	6.64E-04	1.57E-48	8.08E-47	0.00%	2.26E-01	1.43E-48	8.08E-47	1.50E-55	0.00%
Al-27 (g,sp) F-18	7.15E-03	8.01E-08	4.14E-06	0.02%	2.26E-01	7.20E-08	4.14E-06	7.66E-15	0.00%
Al-27 (g,sp) Ne-24	1.58E-04	2.07E-136	1.07E-134	0.00%	2.28E-01	9.96E-137	1.07E-134	1.98E-143	0.00%
Al-27 (g,sp) Na-22	1.85E-05	1.85E-06	9.54E-05	0.42%	1.87E-01	3.42E-06	9.54E-05	1.77E-13	0.00%
Al-27 (g,sp) Na-24	1.28E-02	4.19E-04	2.17E-02	95.74%	1.15E-01	1.21E-03	2.17E-02	4.01E-11	0.00%
Al-27 (g,sp) Al-26	2.31E-09	2.31E-10	1.19E-08	0.00%	1.66E-01	4.97E-10	1.19E-08	2.20E-17	0.00%
Al-27 (g,sp) Al-26m	4.49E-01	0.00E+00	0.00E+00	0.00%	2.26E-01	0.00E+00	0.00E+00	0.00E+00	0.00%
Al-27 (g,sp) Mg-27	8.17E-04	2.00E-50	1.03E-48	0.00%	1.76E-01	1.53E-50	1.03E-48	1.92E-57	0.00%
									0.00%

Figure Captions:

Figure 1: Illustration of the geometry used to calculate the specific activity in air.

Figure 2: An example of the spreadsheet used to calculate the airborne concentrations from welding a volume-activated piece of aluminum with an effective radius of 139 cm. The works of G. Saxon and IAEA Technical Report #188 [Saxon 1969; IAEA 1979] were used in the development of this spreadsheet.